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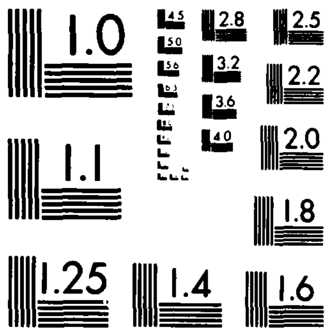

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Utilizing a multiple-element scale/coherence decomposition of the Navier-Stokes equations, the essential characteristics of the large scale turbulent structure are computed in wall-bounded shear flows. The effect of small-scale turbulence structure is modeled and the large-scale turbulence structure is computed assuming weakly non-linear large-scale dynamics. The effects of large-scale non-linearity and the presence of wave-like elements in the flow are accounted for utilizing perturbation theory. The resultant propagation, evolution (in the convected reference frame) and (statistical) occurrence of three-dimensional vartical instabilities are computed and compared to experimental data. Subsequently, coherent structure reflective turbulence models shall be constructed from this analysis.

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COHERENT STRUCTURE REFLECTIVE TURBULENT VISCOUS FLOW MODELING

FINAL REPORT HOKE-84-AF-01
CONTRACT NO.: F49620-84-C-0014
84-01-15 TO 85-01-15

A Multiple-Element Scale/Coherence Decomposition of the Equations of Motion, Analytical/Numerical Prediction of Organized Turbulent Structure Dynamics and Subsequent Anisotropic, Non-Gradient Transport Modeling of High Reynolds Number Flows Over Wings and Bodies.

Phase I: 2-D Constant Pressure Flows

Phase II: Complex Flow

a. Unsteady external flow:
   impulsive, oscillatory, stochastic.

b. Longitudinal curvature:
   leading edge and trailing edge interactions with streamwise and normal pressure gradients.

c. Three-dimensionality:
   including separations.

d. Compressibility:
   including shock interactions.

84-12-15

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TYPICAL EIGEN-AMPLITUDE DISTRIBUTION

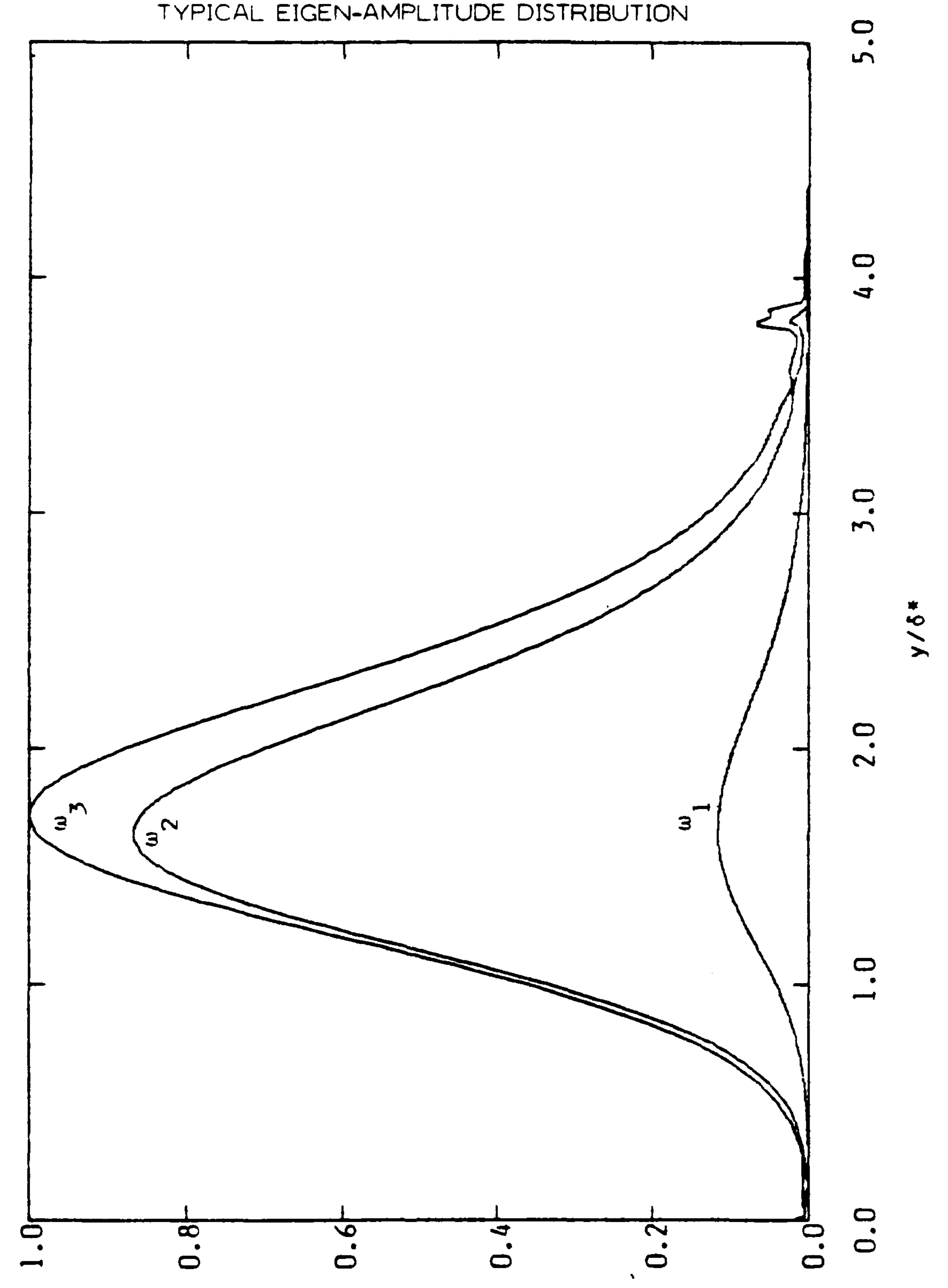


Table of Contents

Page

I. Executive Summary

A multiple-element scale/coherence decomposition of the Navier-Stokes equations is employed to compute the Lagrangian evolutionary dynamics of the dominant three-dimensional, non-linear vortical features in high Reynolds number wall-bounded turbulent shear flows. Organized turbulent and wave-like structures of various scales, their interactions and transitions between them are computed distinctly and subsequently shall be modeled. The resultant model is denoted 'coherent structure-reflective' since it is derived from equations whose prediction of organized turbulence elements (evolution/propagation/occurrence) will have been validated through comparison to observations.

This analysis is carried out initially for constant pressure, two-dimensional boundary layers. The complex effects of a *solid boundary (and its associated* low Reynolds number flow regime) on the difficult instability of a non-inflectional mean turbulent velocity profile indicate the virtues of distinguishing between elements of various scale and coherence. In addition, the work points out the manner in which this approach facilitates treatment of all the original N-S equation non-linearities via:

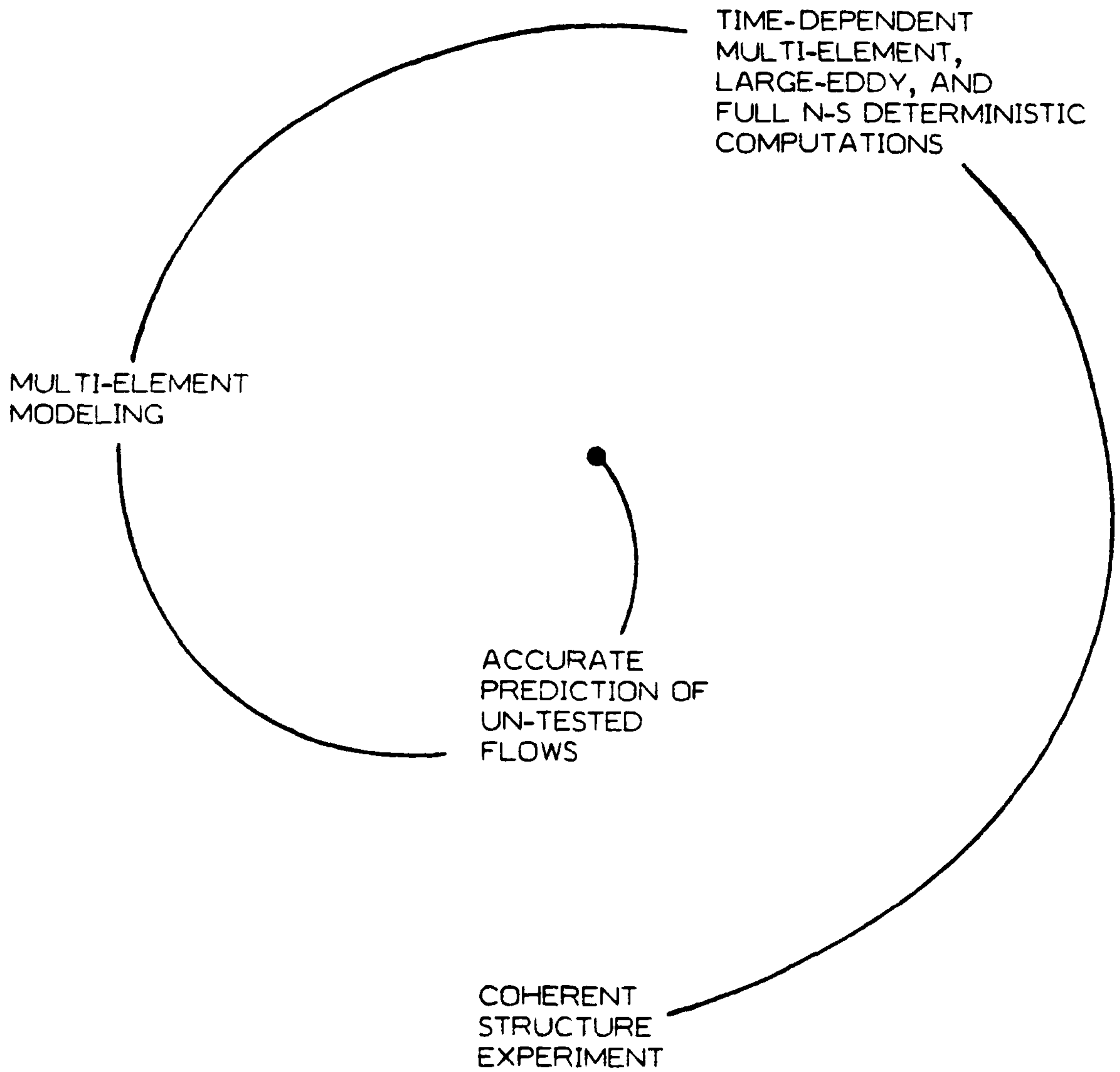
1. The decomposition itself,
2. Perturbations analysis, and
3. Small scale stress/flux modeling.

Subsequent work on complex shear flows involving:

1. Streamwise and normal pressure gradients due to curvature,
2. Unsteady external flow,
3. Three-dimensionality, and
4. Compressibility,

is also amenable to structural computation and modeling which is in accord with observation and the following schematic.

RESEARCH PERSPECTIVE



II. Introduction

The accurate prediction of untested*, high Reynolds number, wall-bounded, turbulent shear flows in complex situations is sought from a new class of representations of the time- or ensemble-averaged flow. Such theoretical formulations are herein denoted as:

"Coherent Structure-Reflective"

in order to emphasize the fact that the various Eulerian closure formulations embody current experimental reality and are derivable from equations/computations of the time-dependent organized turbulent structure and its Lagrangian evolutionary details.

Note that such analyses are important in their own right, apart from subsequent modeling, in the understanding of non-linear vortical dynamics. In fact, the simplest set of equations which contain the essential structural properties required to predict turbulent transport are tested by direct comparison with observations. Following verification, the governing structure equations shall be processed to provide a model which resides somewhere between current multi-equation modeling formulations and LES/full N-S equation solvers (which provide 'typical' turbulent realizations that may be ensembled), benefitting from developments in both fields.

For the foreseeable future, at flight Reynolds numbers of interest, modeling will be required. However, it is the intent of this work to develop formulations more nearly in accord with experimental observations. Improvement in the prediction of these flowfields is achieved by addressing:

*To the extent that insufficient data is available for traditional case-by-case turbulence model 'tuning'.

Multiple-scale,

Anisotropy, and

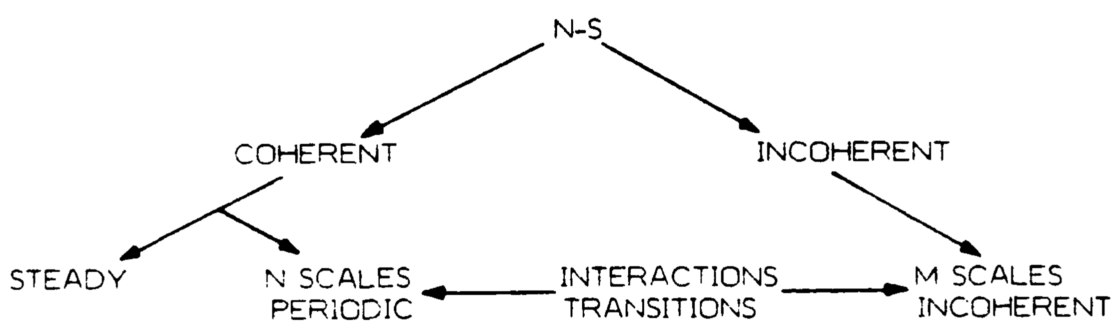
Non-gradient transport,

phenomena directly in the models, in a manner compatible with experimental data and rigorously derived from the deterministic structure dynamics equations developed here. In addition (and particularly for the complex flows to be addressed in subsequent work), the approach is extended to accomodate truly coherent wave-like oscillations due to curvature, unsteady external flow, three-dimensionality, compressibility and low Reynolds number (near-wall) effects.

As a result, the overall procedure is a:

"Multiple-element Turbulence Decomposition",

where uniquenesses of the flowfield structures associated with various scales and coherences, their interactions and transitions between them are computed distinctly (and subsequently modeled) according to the following prescription:



In this methodology, all nonlinearities are accomodated by:

1. The decomposition itself,
2. Perturbation methods, and
3. Modeling small scale stresses/fluxes,

resulting in an expanded set of weakly non-linear equations whose soultion structure is more readily accessible than that of the primitive or sub-grid-scale-modeled large-eddy equations.

The role which observational data or LES/full N-S solutions play in calibrating or verifying this approach is more subtle than in traditional turbulence modeling. The primary difficulty in this regard, even for two-dimensional constant pressure boundary layers, is that conventional modeling is rooted in fundamentals which are not in accord with observation. As a result, extensive empirical adjustment of the various 'constants' and functionals is required to post-dict the experiment from which the models were 'tuned'. The need for calibration is not, however, the Achilles' heel of modeling. The problem is the situ tion-specific tuning of models dictated by the faulty premises on which they are based. Sufficiently general models may require 'tuning' but only in a sing.., simplified flow; ala' the hot-wire anemometer calibration.

For this reason, it is equally as difficult to stretch any single-fluctuating-element two-equation (e.g. k-ϵ) model into being 'coherent structure-reflective' by comparing it with the multiple-element computational results presented here. This is not surprising since these models are grounded in:

1. Essentially isotropic,

2. Single scale, and

3. Gradient transport

notions. (In contrast, free-mixing situations, excepting low Reynolds number regions, are essentially single-scale for which $\tau \sim \rho u' \ell \ \partial u/\partial y$ is not a gradient transport assumption. In these flows, differential equation representation of the length and velocity scales enhances already good predictions by accounting for non-equilibrium effects.) In addition, current Reynolds Stress Tensor models are not sufficently mature for reliable application to complex flows or adaptation to coherent structure reflecive status. Therefore, the bulk of the work reported here focuses not on adjusting other models but on computing coherent structures and formulating models appropriate thereto. The associated validation of coherent structure reflective models is a simple non-iterative comparison with observation or LES/N-S solver results, once it has bee established that the deterministic structural equations are grasping the essence of the three-dimensional, non-linear vortical dynamics. In this regard, some caution must be exercised when comparing computed streaklines to observations and then making inferences about the Lagrangian structures involved.

Apart from the discrepancy between single-scale modeling concepts and multiple-scale flows, another phenomenon arises in wall-bounded situations which adds justification to the scale/coherence decomposition approach developed here. This is associated with the low Reynolds number nature of the near-wall region. In fact, the structure of this unsteady viscous flow is more nearly instability wave-like. Therefore, when representting all appropriate fluctuations in the flow near a wall, both wave-like and turbulent processes may be required. The solid boundary essentially damps the turbulent fluctuations while making the organized oscillations highly anisotropic, clearly a difficult nature for essentially isotropic modeling to accomodate under the single-element modeling umbrella. In fact, this is the reason that ϵ is set equal to zero at the wall, wall, whereas the total dissipation is finite due to anisotropic effects. Therefore, even ignoring the multiple-scale nature, conventional single-element modeling oversimplifies the near wall fluctuations/interactions/transitions. Similar complications arise at the fluctuating interface with the outer flow.

These phenomena indicate the need to apply multi-element modeling to even simple flows*. However, the two-dimensional, constant pressure turbulent boundary layer is an appropriate starting point for the deterministic structural computations of interest here. This is because the turbulent mean velocity profile is non-inflectional and thought to be stable, even to 'apparent viscous' instabilities found in laminar flows. It will be shown that the resolution of this problem is associated with a delicate interplay between.

1. Mean velocity profile details,
2. Small scale stress,
    a. non-equilibrium
    b. anisotropy
3. Non-parallelism, and
4. Non-linearity,

exposed by the scale/coherence decomposition.

*The final (low Reynolds number) stages of even sheared grid turbulence develops highly anisotropic, wave-like structures.

IV.b. The Prescription

In order to implement the physics of Section IV.a. into a comprehensive mathematical model, the following prescription has been devised.

1. Decomposition.

Multi-element decompose the equations of motion to differentiate between events of various scale and coherence, their interactions and transitions between them. Accomodation for, and subsequent modeling of the primitive non-linearities is therely facilitated through:

a. The decomposition itself,

b. Perturbation expansions, and

c. Modeling the small scale stresses/fluxes,

at the price of an expanded (yet simplified and essentially rigorous) set of governing equations as follows:

4. Complex flow.

Wave-turbulence interactions and transitions. Large scale-small scale. Signal-background δ-δ_x (non-parallelism) Remnant 'summing' leads to various added elements u'_α and u'_β , etc.

5. Self-perpetuation.

Remnant summing.

Interactions

1. The superlayer.

High speed (U) external flow 'runs into' high V ejection jets propagating at U/H, partially-entrained and partially disturbed, possibly setting-up the downstream flow with precursor information. Upstream and downstream 'radiation' occurs. The interface between the disturbed external irrotational flow and the rotational shear flow is distinct and a clear transition between differing fluctuating states (coherent vs. incoherent?). The time-average view of a smoothly-varying vorticity is irrelevant.

2. The viscous sublayer.

The region is unsteady and low Reynolds number, indication a distinctly non-chaotic nature. It may be understood in terms of two-layer (i.e. spatially-varying ν) Langmuir rolls and a streaming phenomena as a result of wave-turbulence interactions.

3. Inner flow-outer flow synchronization.

The pressure field and the external flow, which passes over burst events and proceeds downstream, may serve to unify the inner and outer flow.

Vorticity

1. Three-dimensional vortex tilting/stretching and breakdown.

2. Vertical vorticity - vertical velocity resonance/non-linear dispersive wave mechanics.

3. Three-dimensional local separations.

   Curved and sheared flow around 'jets' associated with the fundamental instability may introduce another class of hairpin vortex structure.

4. Langmuir circulation patterns in flows with spatially non-homogeneous ν.

5. Goertler vortices.

Three-dimensionality

1. Three-dimensional boundary layer instability.

2. Three-dimensional local separations.

3. Vertical vorticity - vertical velocity resonance.

4. Helicity.

5. Self-perpetuation.

2. Critical level interactions are significant to understand the fundamental instability.

   'Viscous' and/or non-linear effects are important but the initial value problem nature of the vortex dynamics evolution may also impact the situation.

3. Multiple scale perturbation.

   The fundamental instability drives a free shear layer inviscid instability involving large-scale/small-scale and coherent/incoherent interactions. There is an equivalence between large-scale (residual) non-linearity effects and the effect of: coherent fluctuations on the large scale, large scale fluctuations on the small scale, etc., leading to "multiple-scale perturbation" amplitude envelope evolution problems.

4. Cause/effect vs. non-linear flowfield unity.

   Note that sequential cause-effect within a particular scale/coherence is equivalent to the aforementioned effect of coherent fluctuations on large scales, large scales on small scales, etc.

5. Self-perpetuation.

   In a linear system, no qualitative change in dynamics would occur as a result of turbulent burst structure remnants combining.

carry their own noise generator.) However, like laminar flow, in terms of the given local state (e.g. δ), the typical details can all be specified. But determining the local state requires initial condition and boundary condition (irradiation) statistics and history, including streamwise inhomogeneities and non-equilibrium. Note also that upstream (initial condition contamination) and downstream (precursor) radiation of information is possible due to the fact that the external disturbed (yet not entrained) flow is traveling at U - U/H relative to the L structure.

Non-linearity

1. Small scale non-linear terms are modelable.

According to Landahl, the large-scale structures are weakly non-linear as long as the (background) small-scale 'apparent' stresses/fluxes or sources/sinks are accounted for in the various interactions/transitions. Very fine scale effects may simply reduce the effective Reynolds number but caution must be exercised when adding ν_t to ν. Clearly, the small-scale non-linearities are non-equilibrium, possibly anisotropic, not necessarily Newtonian and Reynolds number-dependent. ν_t gradients (μ_t and/or ρ) lead to streamwise vorticity, reminiscent of Langmuir circulations.

The initial condition variability and selective amplification of ambient or self-induced radiation also have counterparts in the rain-field. The abstract result is a non-linear box with multiple feedback, pure tone excitation and expansion/compression (i.e. amplitude-dependent amplification).

3. Propagation dynamics of large-scale structures.

The streamwise propagation of large-scale structures is understandable in terms of the equation:

$$L_{,t} + (U/H)L_{,x} = fL + g \ ,$$

which is the familiar time-dependent integral TBL equation if $L = \Theta$ and $g = C_f$. The resultant space-time focusing and wave-like (vs. diffusive) nature of these non-linear dispersive phenomena is accessible from such an equation.

4. Observed 'complex' streaklines/pathlines/vortex lines may arise from simple streamlines, thus pointing out the importance of the right viewing reference.

5. Independence of initial conditions.

If the initial conditions (for the wave instability and coalescence) are the only source of irregularity, the solution is not strictly independent of initial conditions. (Note that all numerical schemes 'viscous'* and, possibly, non-parallel and non-linear (threshold/ hypteresis) effects. Note that experimental data may suffer some spatial/temporal 'smearing' due to the signal processing. Subsequent to the discovery of a fundamental mean profile distortion instability is a secondary free-shear layer inviscid instability, due to non-linear mean profile distortion, resulting in a multiple-scale perturbation amplitude evolution problem.

2. Chaotic/statistical occurence of organized structures.

Ala' the rain-field model, this may be the natural mathematical state of weakly-constrained continuous vector fields, as indicated by strange attractor theory. Clearly, our Eulerian point of view is deceiving and unnecessarily complicating, as the raindrop model makes clear. (An alternative metaphorical view of turbulence is related to traffic flow which points up the need for a Lagrangian approach. Conditionally-sampled data is inevitably an average over various typical turbulent structures and distinctions between, e.g., trucks, buses and cars are smeared out.) Turbulent flow 'patchiness' is clearly more readily described by fractals or pdf's which depend on (flow) historical inputs regarding instability thresholds and hysteresis, size/speed variability and a metastable nature. Interactions between burst structure remnants into a disturbance of sufficient 'size' is represented by the various non-linear terms.

*Note gradients in μ and/or ρ are secondary vorticity-inducing and streamwise vorticity acts like enhanced transport to the large scale flow.

This process continues as long as the raindrops have potential energy, and there is no surprise that perpetuation and statistically-scattered impact occur. Similarly, once turbulent flow instability waves coalesce (irregularly, dependent on statistically-distributed nucleation sites), their propagation/interaction and bursting instability proceeds as long as the main flow has kinetic energy and is unstable.

Following the rain-field analogy a step further, it is sufficient (for the composition of a comprehensive model) to assess deterministic raindrop propagation, interactions and instability following a given organized structure. Subsequently, it is possible to assemble a statistical model of drop and burst occurence based on variability in the coalescence initial conditions and various threshold/hysteresis effects in the individual droplet dynamics.

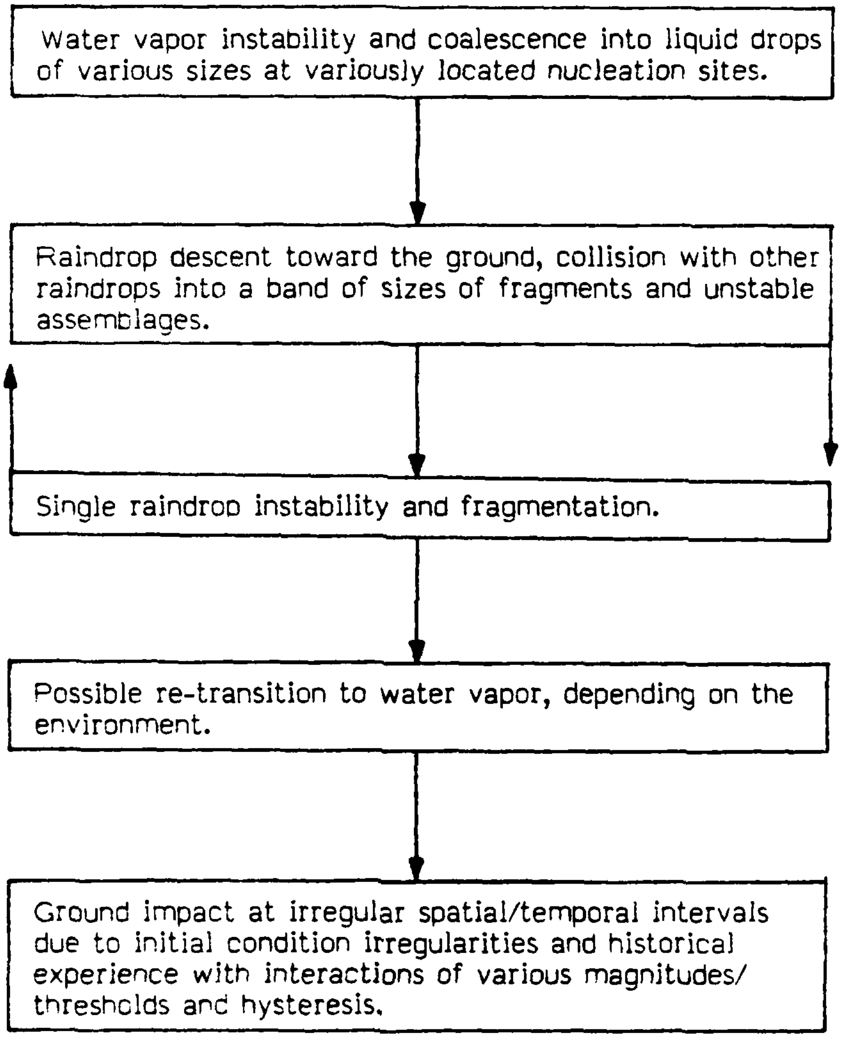
Returning now to the non-global details, several features of the TBL flow are enumerated here, in accord with the previous definition, which are part of the long-range focus of this research:

Time-dependence

1. Periodically-inflectional conditionally-sampled mean TBL velocity profile.

   The time-averaged mean profile is non-inflectional and thought to be stable. Therefore, primary instability must be related to the small-scale non-linear terms (stresses/fluxes or sources/sinks) ala' laminar boundary layers. Conditionally-sampled structure data should be compatible with computations utilizing non-equilibrium/non-uniform

RAIN-FIELD 'TURBULENCE'



IV.a. The Building Blocks

When attempting to assemble a comprehensive representation of turbulence which is in accord with, and reflects organized structure physics, it is appropriate to catalog and examine the various proven or proposed component processes. It may seem trite, but it is useful for organization, to define turbulence as complex time-dependent, non-linear, three-dimensional, vortical interactions. In the process of documenting the content of the multi-element scale/coherence approach, various phenomena which are confronted fit within one or more of these categories.

Overlaying many of these phenomena is a global view of turbulence, similar in some regards to the following raindrop/rain-field scenario:

IV. Results

The research work presented here involves analytical/computational investigations of various aspects of the evolution (in the convected frame), propagation and statistical occurrence of large scale structures in a TBL flow. Prior to the presentations of calculations, sections which describe the building blocks of the analysis, the computational prescription and an enumeration of the various facets of the mathematics and physics which this approach seeks to embrace are presented.

The secondary objective of this work is to lay the foundation for multi-element computations of turbulent structure and subsequent modeling of more complex flows. Specifically, the intent is to address the effects of:

1. Longitudinal curvature- including: strong P_y and P_x; Possible re-transition/waves and localized separation at the leading edge; non-boundary layer wake interaction/separation/Goertler vortices formation at the trailing edge,

2. Unsteady external flow- impulsive, periodic and stochastic,

3. Three-dimensionality- including separation bubbles, and

4. Compressibility- vorticity/dilatation/pressure fluctuation interactions of various scales,

These phenomena shall be superposed (not necessarily linearly of simply) on the two-dimensional constant pressure boundary layer has been studied preliminarily in this first year of research.

III. Objectives

The primary objective of this multi-year research effort is to compute turbulent structural characteristics and integrate them into models of the flow such that accurate predictions of untested situations are possible without case-by-case 'tuning'. Traditionally, Eulerian flowfield predictions focus directly on computing surface stress (including pressure for viscous interaction cases) and flux distributions, from which they were tuned, such that the forces, heat loads and wake signature characteristics may be computed. Ideally, the modeling may eventually become sufficiently general to accomodate local or massive separations and all of the complex effects of interest in the subsequent phases of this research.

In order to achieve a reliable model of the turbulence which provides such predictions, we seek to compute Lagrangian turbulence structural details (evolution/propagation/occurrence), building the foundation of the turbulent stress/flux representations with the requisite:

1. Multiple scale,
2. Anisotropic, and
3. Non-gradient transport

nature and accomodating both turbulent and non-turbulent fluctuations. Subsequently, ability to fabricate models directly from the multi-element structural equations shall be assessed.

TYPICAL FOUR - ELEMENT SCALE/COHERENCE DECOMPOSITION

$$\text{Decomposition:}\quad u_i = \bar{U}_i + \tilde{U}_i + (U_i' + u_i')$$

$$p = \bar{P} + \tilde{P} + (P' + p')$$

MEAN FLOW

$$\bar{U}_j \frac{\partial \bar{U}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{P}}{\partial x_i} + \nu \frac{\partial^2 \bar{U}_i}{\partial x_j \partial x_j} - \frac{\partial}{\partial x_j}\left(\overline{\tilde{U}_i \tilde{U}_j + U_i' U_j' + u_i' u_j'}\right)$$

$$\frac{\partial U_i}{\partial x_i} = 0$$

WAVE - LIKE FLOW

$$\frac{\partial \tilde{U}_i}{\partial t} + \bar{U}_j \frac{\partial \tilde{U}_i}{\partial x_j} + \tilde{U}_j \frac{\partial \bar{U}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \tilde{P}}{\partial x_i} + \nu \frac{\partial^2 \tilde{U}_i}{\partial x_j \partial x_j} - \frac{\partial}{\partial x_j}\left[\overset{\checkmark}{(\tilde{U}_i \tilde{U}_j - \overline{\tilde{U}_i \tilde{U}_j})} + \overset{\tilde{r}_{ij}}{(\langle U_i' U_j'\rangle - \overline{U_i' U_j'})} + \overset{\downarrow}{(\langle u_i' u_j'\rangle - \overline{u_i' u_j'})}\right]$$

$$\frac{\partial \tilde{U}_i}{\partial x_i} = 0$$

TURBULENT FLOW

Large Scale

$$\frac{\partial U_i'}{\partial t} + (\bar{U}_j + \underset{\uparrow}{\tilde{U}_j})\frac{\partial U_i'}{\partial x_j} + U_j' \frac{\partial}{\partial x_j}(\bar{U}_i + \underset{\uparrow}{\tilde{U}_i}) = -\frac{1}{\rho}\frac{\partial P'}{\partial x_i} + \nu \frac{\partial^2 U_i'}{\partial x_j \partial x_j} - \frac{\partial}{\partial x_j}\left[\overset{\checkmark}{(U_i' U_j' - \langle U_i' U_j'\rangle)} + \overset{\downarrow}{(u_i' u_j' - \langle u_i' u_j'\rangle)}\right]$$

$$\frac{\partial U_i'}{\partial x_i} = 0$$

Small Scale

$$\frac{\partial u_i'}{\partial t} + (\bar{U}_j + \underset{\uparrow}{\tilde{U}_j} + U_j')\frac{\partial u_i'}{\partial x_j} + u' \frac{\partial}{\partial x_j}(\bar{U}_i + \underset{\uparrow}{\tilde{U}_i} + U_i') = -\frac{1}{\rho}\frac{\partial p'}{\partial x_i} + \nu \frac{\partial^2 u_i'}{\partial x_j \partial x_j} - \frac{\partial}{\partial x_j}\left[\overset{\checkmark}{(u_i' u_j' - \langle u_i' u_j'\rangle)} - \overset{\downarrow}{(u_i' u_j' - \langle u_i' u_j'\rangle)}\right]$$

$$\frac{\partial u_i'}{\partial x_i} = 0$$

Note: N.L. Terms: Retained $\uparrow$

Modeled $\downarrow$

Accounted for by Perturbation $\checkmark$

TYPICAL WAVE - TURBULENCE INTERACTION SIMPLIFICATION

$$\frac{D\tilde{r}_{ij}}{Dt}+\tilde{u}_k\frac{\partial\tilde{r}_{ij}}{\partial x_k}+\tilde{u}_k\frac{\partial}{\partial x_k}(u_i'u_j')+\tilde{r}_{jk}\frac{\partial U_i}{\partial x_k}+\tilde{r}_{ik}\frac{\partial U_j}{\partial x_k}+u_j'u_k'\frac{\partial\tilde{u}_i}{\partial x_k}+u_i'u_k'\frac{\partial\tilde{u}_j}{\partial x_k}$$

$$= -\tilde{r}_{jk}\frac{\partial\tilde{u}_i}{\partial x_k}+\overline{\tilde{r}_{jk}\frac{\partial\tilde{u}_i}{\partial x_k}}-\tilde{r}_{ik}\frac{\partial\tilde{u}_j}{\partial x_k}+\overline{\tilde{r}_{ik}\frac{\partial\tilde{u}_j}{\partial x_k}}+\overline{\tilde{u}_k\frac{\partial}{\partial x_k}\tilde{r}_{ij}}+\frac{\partial}{\partial x_k}(u_i'u_j'u_k'-\langle u_i'u_j'u_k'\rangle)-$$

$$-\left\langle u_j'\frac{\partial p'}{\partial x_i}\right\rangle+\overline{u_j'\frac{\partial p'}{\partial x_i}}-\left\langle u_i'\frac{\partial p'}{\partial x_j}\right\rangle+\overline{u_i'\frac{\partial p'}{\partial x_j}}+\frac{1}{T_0}\{g(\langle\theta'u_j'\rangle-\overline{\theta'u_j'})\delta_{i3}+$$

$$+g(\langle\theta'u_i'\rangle-\overline{\theta'u_i'})\delta_{j3}\}+\text{ viscous terms}. \qquad . \qquad . \qquad . \qquad .$$

$$\overset{1\cdot 0}{\frac{\partial\tilde{r}_{13}}{\partial t}}+\overset{0\cdot 08}{U_1\frac{\partial\tilde{r}_{13}}{\partial x_1}}+\overset{0\cdot 07}{\tilde{u}_3\frac{\partial\tilde{r}_{13}}{\partial x_3}}+\overset{0\cdot 01}{\tilde{u}_3\frac{\partial}{\partial x_3}\overline{u_1'u_3'}}+\overset{0\cdot 4}{\tilde{r}_{33}\frac{\partial U_1}{\partial x_3}}+\overset{0\cdot 06}{\overline{u_3'^2}\frac{\partial\tilde{u}_1}{\partial x_3}}+\overset{0\cdot 01}{\overline{u_1'u_3'}\frac{\partial\tilde{u}_3}{\partial x_3}}$$

$$= \overset{0\cdot 15}{-\tilde{r}_{33}\frac{\partial\tilde{u}_1}{\partial x_3}}+\overset{0\cdot 001}{\overline{\tilde{r}_{33}\frac{\partial\tilde{u}_1}{\partial x_3}}}-\overset{0\cdot 06}{\tilde{r}_{13}\frac{\partial\tilde{u}_3}{\partial x_3}}+\overset{0\cdot 001}{\overline{\tilde{r}_{13}\frac{\partial\tilde{u}_3}{\partial x_3}}}+\overset{0\cdot 001}{\overline{\tilde{u}_3\frac{\partial\tilde{r}_{13}}{\partial x_3}}}+$$

$$\overset{0\cdot 04}{\frac{\partial}{\partial x_3}(\overline{u_1'u_3'^2}-\langle u_1'u_3'^2\rangle)}-\overset{\text{pressure gradient term (PG): magnitude unknown}}{\left(\left\langle u_3'\frac{\partial p'}{\partial x_1}\right\rangle-\overline{u_3'\frac{\partial p'}{\partial x_1}}+\left\langle u_1'\frac{\partial p'}{\partial x_3}\right\rangle-\overline{u_1'\frac{\partial p'}{\partial x_3}}\right)}+$$

$$+\overset{0\cdot 05}{\frac{g}{T_0}(\langle u_1'\theta'\rangle-\overline{u_1'\theta'})} \qquad . \qquad . \qquad . \qquad . \qquad . \qquad .$$

$$\frac{\partial\tilde{r}_{13}}{\partial t}+\tilde{r}_{33}\frac{\partial U_1}{\partial x_3} = \text{pressure terms}$$

$$\frac{\partial_2\tilde{r}_3}{\partial t}+\tilde{r}_{33}\frac{\partial U_2}{\partial x_3} = \text{pressure terms}$$

$$\frac{\partial\tilde{r}_{11}}{\partial t}+2\tilde{r}_{13}\frac{\partial U_1}{\partial x_3} = \text{pressure terms}$$

$$\frac{\partial\tilde{r}_{33}}{\partial t} = \text{pressure terms}$$

2. Solve large scale structure <u>evolution</u> equations and compare results to experimental streaklines.

3. Compute 'details':

   a. Primary distortion and secondary free shear layer instability amplitude evolution.

   b. Sublayer vortices - wavy and acting as effective variable ν in small scale stresses? Superlayer waviness - entrainment.

   c. Vertical velocity - vertical vorticity interaction/resonance.

   d. Non-linear wave-turbulence interactions/transitions.

   e. Three-dimensional separation-type vorticity generated by curved sheared flow?

4. Evaluate <u>propagational</u> characteristics of large-scale structures.

5. Evaluate statistical <u>occurrence</u>: pdf and fractals.

6. *Average/model the verified large-scale structure governing equations based on structural event computations.

7. Compute the mean flow with a coherent structure reflective stress model.

8. Evaluate modeling sensitivities.

*Items 6 - 10 are the subject of on-going research.

9. Compute modeled small scale non-linear terms to determine if modeling constants are universal.

10. Compute non-linear interactions/transitions to verify the validity of perturbation procedures, as applied to the multi-element decomposed equations.

IV.c. Computed Details

During the first year of work on this research the bulk of the effort has been directed at the various analytical formulations and numerical codes required to implement the previously-discussed prescription. The preliminary results to be discussed shall be considerably supplemented in future research reports as the aforementioned research tools are refined and made more productive. The scope of the work being carried out encompasses:

I. Large Scale Structure Analysis/Computations

II. Pathline/Streakline Computations

III. Generic Transport Equation Analysis/Computations

With regard to the item I., the first phase of the large scale structure computations is complete, utilizing the multi-element scale/coherence decomposition approach. The computation of large scale structures has been carried out utilizing the following vorticity equations:

$$\left\{(\bar{u}-c) + \frac{i}{\alpha}\left[(Re^{-1}+\epsilon)(D^2-k^2) + (D^2\epsilon)\right]\right\}\hat{\omega}_1 = -\left\{(D\bar{u}) + \frac{i}{\alpha}(D\epsilon)(2D^2-k^2)\right\}\hat{u}_3$$

$$- \frac{\beta}{\alpha}\left\{(D\epsilon)D - (2D^2\epsilon)\right\}\hat{u}_2$$

$$\left\{(\bar{u}-c) + \frac{i}{\alpha}\left[(Re^{-1}+\epsilon)(D^2-k^2) + (D\epsilon)D\right]\right\}\hat{\omega}_2 = -\frac{\beta}{\alpha}(D\bar{u})\hat{u}_2$$

$$\left\{(\bar{u}-c) + \frac{i}{\alpha}\left[(Re^{-1}+\epsilon)(D^2-k^2) + (D^2\epsilon)\right]\right\}\hat{\omega}_3 = \left\{(D\bar{u}) + \frac{i}{\alpha}(D\epsilon)(2D^2-k^2)\right\}\hat{u}_1$$

$$+ \left\{(D\epsilon)D - (2D^2\epsilon)\right\}\hat{u}_2$$

$$+ \left\{-\frac{i}{\alpha}\left[D^2\bar{u} + (D\bar{u})D\right]\right\}\hat{u}_2$$

These equations are derived from the previously-presented scale/coherence decomposed equations and accomodate:

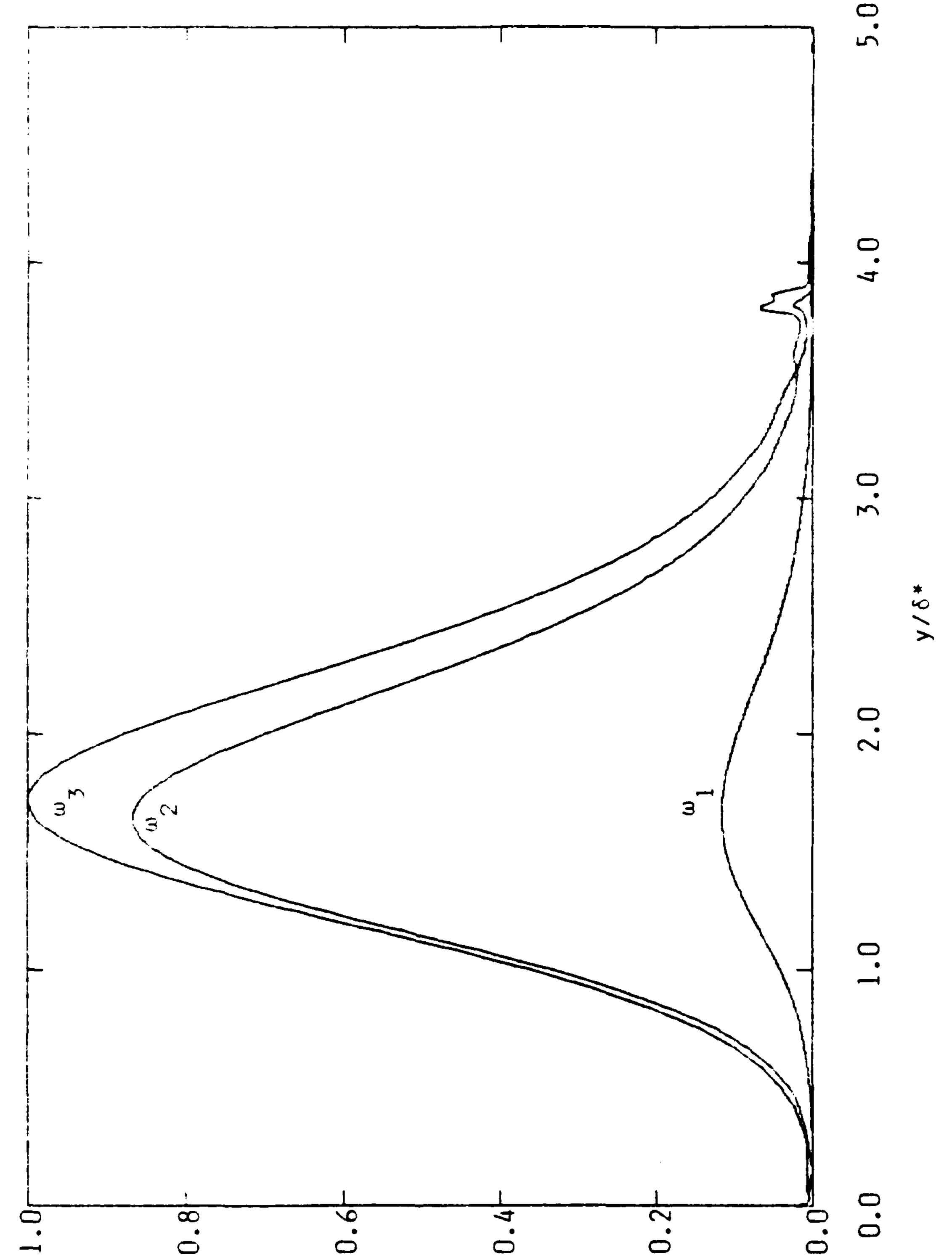
a. spatially-varying, non-equilibrium small-scale processes

b. multiple-scale perturbation analysis of residual non-linearity and wave-like flow component distortion effects (see discussion on III.)

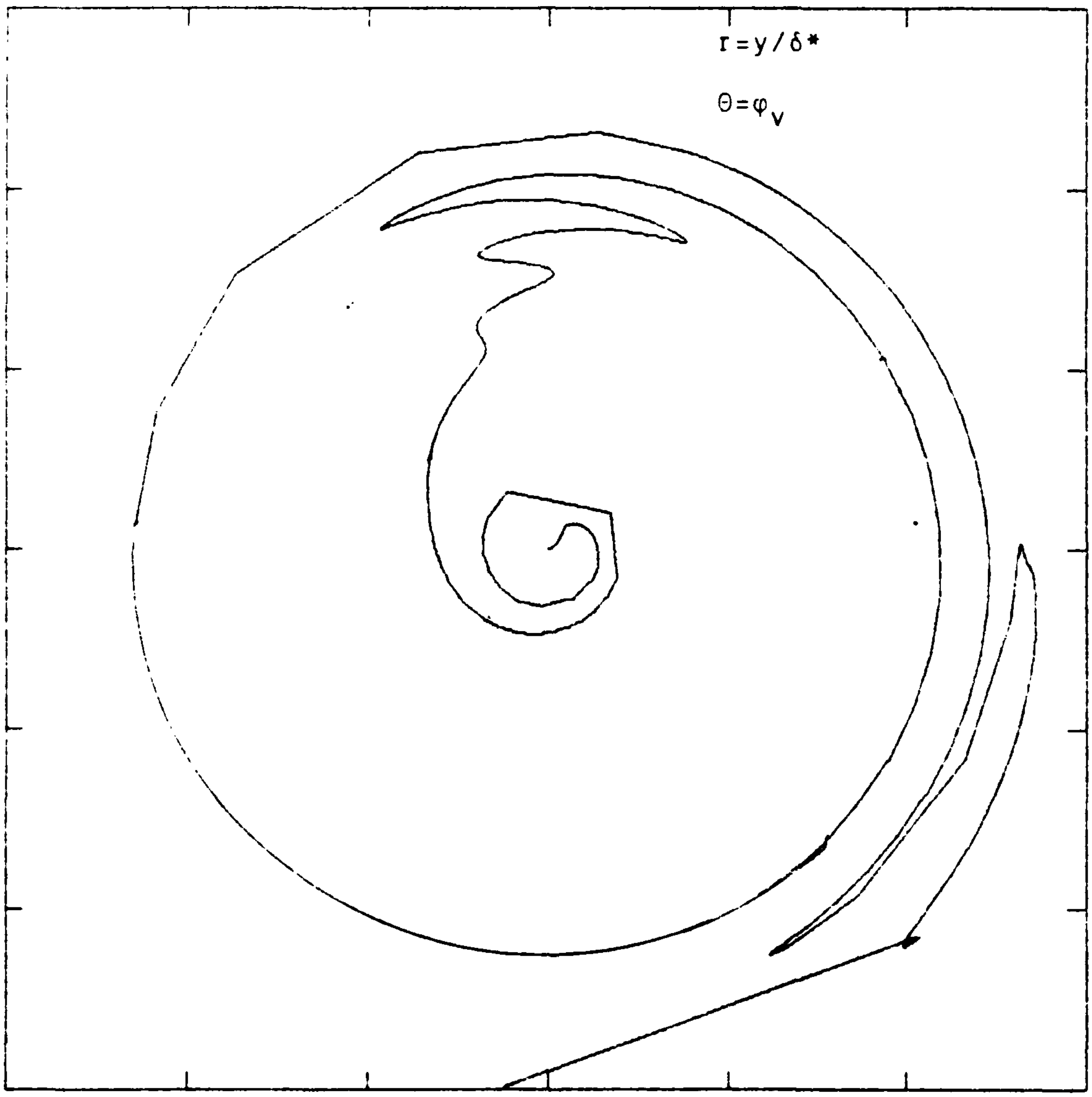
c. evaluation of vertical velocity-vertical vorticity interaction/resonance.

The following results for a typical mode (including only small scale process non-linearity) illustrate the amplitude and phase distributions of the vorticities and vertical velocity in the absence of waves and large scale structure non-linearity. A simplified Newtonian model is used for $\tilde{\tau}_{ij}$. One developing hypothesis of the work is that phase coherence (at a stationary phase value) at various locations across the flow is indicative of significant interactions which the pathlines should reflect. Also, the modal assemblage (in a manner which equates temporal and local spatial average, or overall spatial average for parallel flow) could be guided by such coherence. The frequency, wave number and spatial location in the shear layer of the most unstable mode is in agreement with experimental data.

TYPICAL EIGEN-AMPLITUDE DISTRIBUTION

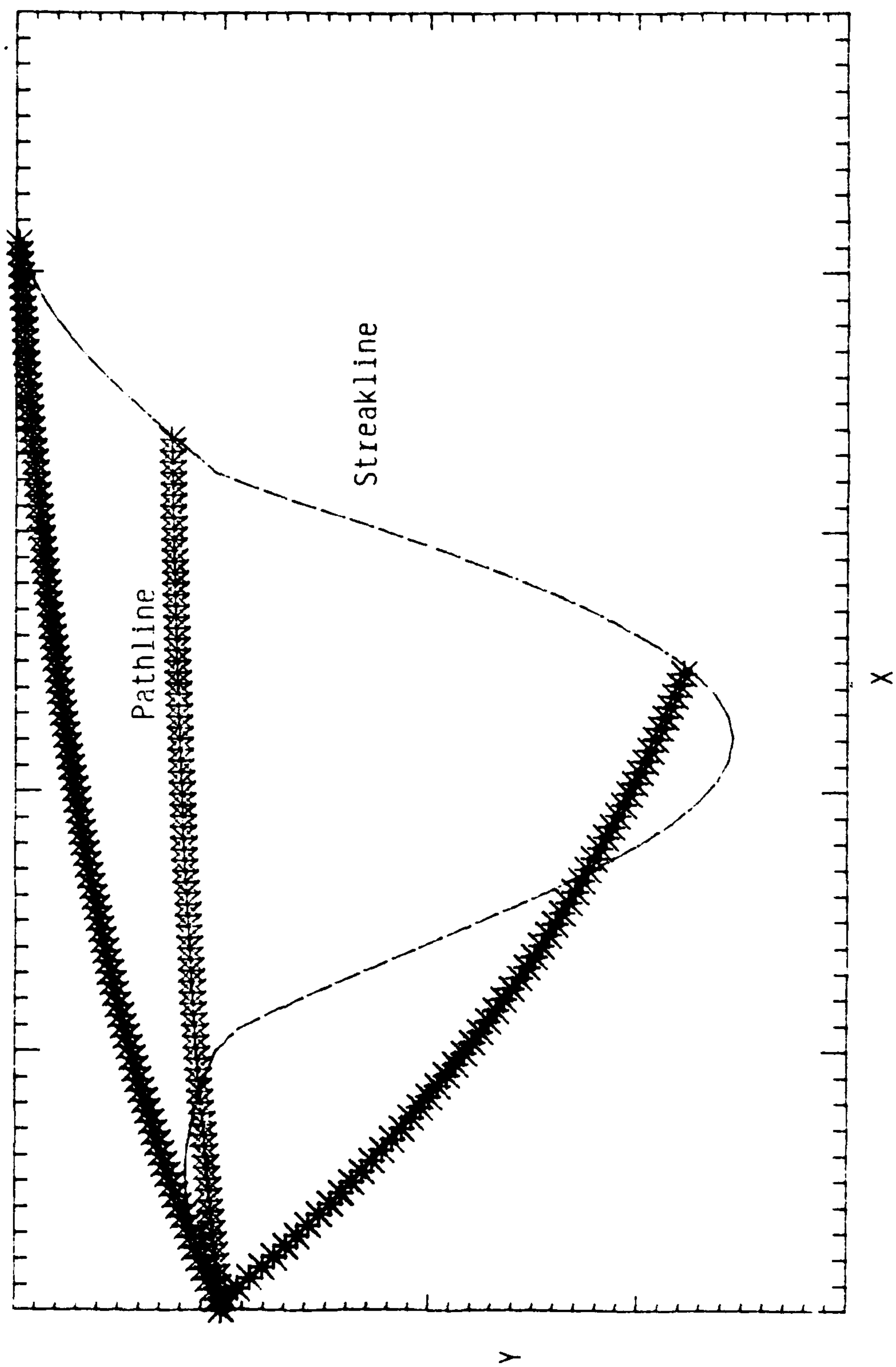


TYPICAL EIGEN-PHASE DISTRIBUTION



The second area of study is the generation and interpretation of three-dimensional pathlines and streaklines from the results computed in I. A typical result which presents a two-dimensional cut through the flow is presented here. Ideally, comparison between experimental and theoretical streaklines will serve to validate the analysis and interpret the data.

TYPICAL 2-D CUT THROUGH A 3-D STREAKLINE FIELD



Finally, the following generic transport equation:

$$L,_t + (U/H)L,_x = fL + g ,$$

where g exhibits a weak inverse dependence on L, is being analyzed/computed with respect to the role it plays in:

a. amplitude evolution of secondary instabilities-
   residual non-linearity plus wave-like distortion,

b. occurrence statistics,

c. propagation dynamics, and

d. general transient boundary layer behavior.

By utilizing a multiple-scale perturbation approach, the secondary instability amplitude evolution, for both large-scale non-linearity and the presence of waves, is found to obey the following equation:

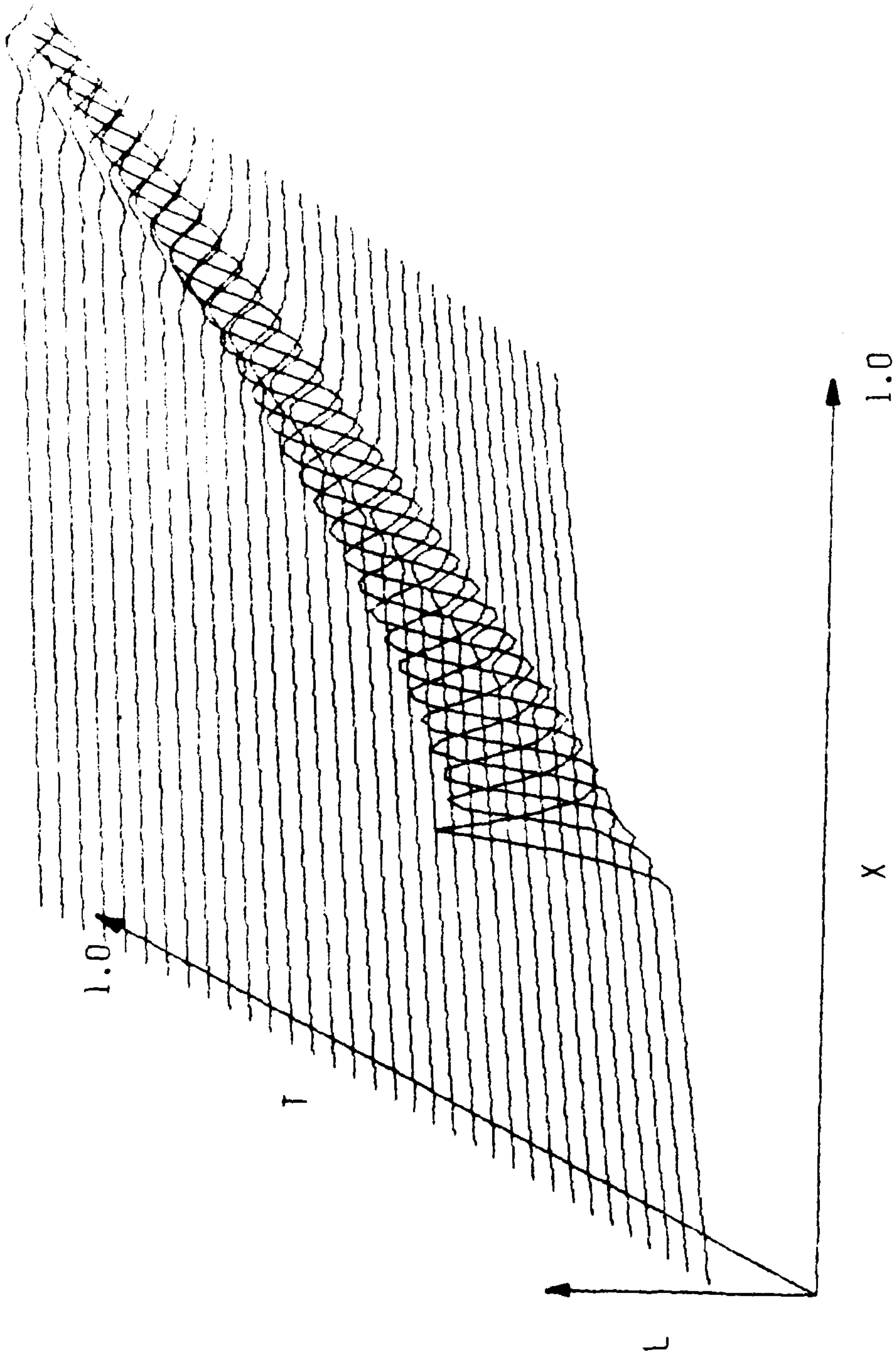
$$S,_T + (\partial f/\partial \omega)^{-1} S,_X = aS + bS^*$$

In addition, current work on pdf representations:

$$-\bar{\rho}\frac{\partial \tilde{P}}{\partial t} + \frac{\partial}{\partial x_i}\frac{\mu_{eff}}{\sigma_p}\frac{\partial \tilde{P}}{\partial x_i} - \bar{\rho}\tilde{u}_i\frac{\partial \tilde{P}}{\partial x_i} - \bar{\rho}\frac{\Gamma_0}{\tau_f}\tilde{P} = -\frac{\bar{\rho}\Gamma_0}{\tau_f}\left[\int_0^z dz'\tilde{P}_f(z')\int_z^1 dz''\tilde{P}_f(z'')\tilde{P}(z',z'',z)\right] + \bar{\rho}\frac{\partial}{\partial z}\left(\frac{S_0(z)}{\rho(z)}\tilde{P}\right)$$

leads to a similar formulation. Finally, if L is identified with any boundary layer integral thickness, the equation may be used to investigate the propagation of 'bulges' in the flow and, subsequently, 3-D interactions between laterally-displaced structures which are advecting principally in the streamwise direction. At present, computations are focusing on obtaining stable solutions with large-amplitude disturbances for which traditional stability theory is not rigorously valid.

TYPICAL BOUNDARY LAYER BULGE PROPAGATION



V. Conclusion

On-going work involves extensive exercise of the tools described here and the inclusion of the presence of wave-like elements and large-scale non-linearity through a multiple-scale perturbation approach. In addition, the optimal representation of $\tilde{r}_{ij}$ is being studied in preparation for follow-on research in variable-pressure flows.

VI. Bibliography

1. Blackwelder, R.F., "The Bursting Process in Turbulent Boundary Layers," AFOSR Lehigh Workshop, 1981.

2. Brown, G.L. and Thomas, A.S.W., "Large Structure in a Turbulent Boundary Layer," The Physics of Fluids, Vol. 20, No. 10, Pt. 11, October 1977.

3. Bull, M.K., "Wall-Pressure Fluctuations Associated with Subsonic Turbulent Boundary Layer Flow," JFM, Vol. 28, Part 4, pp. 719-754, 1967.

4. Falco, R.E., "The Role of Outer Flow Coherent Motions in the Production of Turbulence Near a Wall," AFOSR Lehigh Conference, 1978.

5. Kim, H.T., Kline, S.J. and Reynolds, W.C., "The Production of Turbulence Near a Smooth Wall in a Turbulent Boundary Layer," JFM, Vol. 50, Part 1, pp. 133-160, 1971.

6. Kline, S.J., Reynolds, W.C., Schraub, F.A. and Runstadler, P.W., "The Structure of Turbulent Boundary Layers," JFM, Vol. 30, Part 4, pp. 741-773, 1967.

7. Kovasznay, L.S.G., Kibens, Valdis and Blackwelder, R.F., "Large-Scale Motion in the Intermittent Region of a Turbulent Boundary Layer," JFM, Vol. 41, Part 2, pp. 283-325, 1970.

8. Landahl, M.T., "Recent Developments in Turbulence Research," Opening General Lecture.

9. Mollo-Christensen, E., "Physics of Turbulent Flow," AIAA J., Vol. 9, No. 7, 1971.

10. Narayanan, M.A. Badri and Marvin, Joseph G., "On the Period of the Coherent Structure in Boundary Layers at Large Reynolds Numbers," AFOSR Lehigh Conference, 1978.

11. Offen, G.R. and Kline, S.J., "Experiments on the Velocity Characteristics of 'Bursts' and on the Interactions Between the Inner and Outer Regions of a Turbulent Boundary Layer," Stanford Report MD-31, December 1973.

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